Characteristics of Fe Ablation Trails Observed During the 1998 Leonid Meteor Shower

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Abstract. Eighteen Fe ablation trails were observed during the 17/18 Nov 1998 Leonid meteor shower with an airborne Fe lidar aboard the NSF/NCAR Electra aircraft over Okinawa. The average altitude of the 18 trails from the high velocity (72 km/s) Leonid meteors, 95.67±0.93 km, is approximately 6.7 km higher than previously observed for slower (~30 km/s) sporadic meteors. This height difference is consistent with the assumption that meteors ablate when the kinetic energy imparted to the atmosphere reaches a critical threshold. The average age of the Fe trails, determined by a diffusion model, is 10.1 min. The youngest ages were observed below 92 km and above 98 km where chemistry and diffusion dominate, respectively. The average abundance of the trails is 10% of the abundance of the background Fe layer. Observations suggest that the 1998 Leonid shower did not have a significant impact on the abundance of the background Fe layer.

Introduction

The 1998 and 1999 Leonid meteor showers are unique because the high fluxes of visible meteors make it worthwhile to assemble instruments at common locations to observe the events. This provides an opportunity to study the effects of the meteors on the upper atmosphere and the fate of the deposits of particular interest in the origin of life. Only during a meteor storm is the influx of matter significantly different from the normal sporadic background. The 1998 Leonid shower was the best since the storm of 1966. A composite profile relatively rich in brighter meteors was observed rather than a classical storm component rich in faint meteors. Zenith Hourly Rates increased to 200/hr at around 20:30 UT on Nov. 17. A second broad component rich in bright meteors peaked around 04:30 UT on Nov. 17, half a day earlier [*Jenniskens and Butow*, 1999].

Our group deployed an airborne zenith pointing Fe lidar in Okinawa (26.3°N, 127.7°E) as part of the 1998 Leonid Multi-Instrument Aircraft Campaign (1998 Leonid MAC) [*Jenniskens and Butow*, 1999]. The peak of the shower occurred in the last hour of our flight in the early morning of 18 Nov local time. The lidar observations were complemented by a wide variety of imaging and spectroscopic measurements. This was NASA's first Astrobiology Mission aimed at furthering our understanding of the fate of extraterrestrial materials accreting into Earth's atmosphere. In this paper we report the general characteristics of the Fe ablation trails and the Fe background layer during the Leonid shower and compare them with previous observations of sporadic meteors and of the mesospheric metal layers.

Experimental Configurations

The University of Illinois Fe Boltzmann Temperature lidar was installed on the NSF/NCAR Electra aircraft. This system is actually two complete zenith pointing lidars. Normally one operates at the 372 nm Fe resonance line and the other at the 374 nm Fe line. By ratioing the signals it is possible to derive temperature [*Gelbwachs*, 1994]. For the Leonid experiment, the 374 nm channel was detuned in an attempt to observe any dust or smoke associated with the shower. Thus it was only possible to measure Fe density profiles during the Leonid flight. Each laser operates at about 33 pps with an output power of between 3 and 4 W in the UV. The beam divergence is approximately 1 mrad full width @ e^{-2}. Each telescope is 0.4 m diameter and is optimized for near UV operation. During the Leonid flight the vertical resolution was 24 m and the integration period was 10 s. A variety of other instruments were also deployed on the Electra including an allsky OH imager and a high definition TV camera boresighted with the lidar [*Jenniskens and Butow*, 1999].

Observations

During the eight hour Leonid flight, 18 meteor ablation trails were observed with the Fe lidar. One of the most dense meteor trails probed by the airborne lidar over Okinawa is plotted in Fig. 1. The measured characteristics of all the trails are tabulated in Table 1. The duration is the amount of time a given trail was observed by the lidar system. Most of the other parameters were determined using the meteor trail profile exhibiting the highest abundance. The aircraft altitude varied between 6 and 7 km so that the beam diameter at the altitude of the trails was about 90 m (full width @ e^{-2}) which is about 1/4 the mean diameter of the observed ablation trails. Because of the high aircraft

Fig. 1

Table 1

velocity ($\sim$150 m/s) and narrow diameter of the meteor trails, several only appeared in a single 10 s lidar profile. For these short duration trails, the measured Fe abundance in the trail is a lower bound.

The abundance of the background Fe layer varies seasonally at mid-latitudes in the northern hemisphere with maximum values in November averaging 1.5×10^{10} cm^{-2} [*Kane and Gardner*, 1993a]. The average abundances of the background Fe layer measured during Leonid MAC on and off the peak night are plotted versus date in Fig. 2. They are comparable to the Nov mean at mid-latitudes and were computed between 0200 and 0400 LT to minimize biases associated with tides and other diurnal effects. The marginally higher abundance on 18 Nov is associated with a sporadic Fe layer (see Fig. 1) which was not observed on the other dates. The fresh debris deposited by the Leonid shower did not have a significant effect on the background Fe abundance. However, the mean abundance of the 18 trails observed during the flight ($\sim$10^9 cm^{-2}) was about 10% of the background. One trail had an abundance comparable to the background Fe layer.

Fig. 2

High temperatures associated with frictional heating vaporize meteors as they enter the atmosphere as well as ionize the meteoric material and atmospheric constituents along their paths. Neutralization occurs quickly (less than 1 s) because of the high electron densities in the trail. Initially the neutral Fe is deposited in a trail probably no more than a few meters in diameter /citeJones95. Molecular diffusion then causes the trail broaden both vertically and horizontally so that the Fe concentration nominally assumes a Gaussian profile with a mean square radius ($e^{-1/2}$ radius) (σ^2) that increases linearly with time [*Hoffner et al.*, 1999; *Grime et al.*, 1999a],

$$\sigma^2 = 2Dt + \sigma_0^2 \qquad (1)$$

where D is the molecular diffusivity, t is the elapsed time since ablation, and σ_0 is the initial ablation trail radius. We define the age of a meteor trail as the elapsed time between ablation and observation with the lidar. Molecular diffusivity depends primarily on atmospheric density and temperature and can be modeled with high accuracy. Thus the age of a meteor trail can be estimated by measuring its RMS width using model values for the molecular diffusivity in (1) and assuming the initial trail radius is negligible. This approach was validated using Na lidar observations at Starfire Optical Range, NM where the times of the initial fireballs were recorded and the persistent trails were observed for as long as 30 min [*Chu et al.*, 1999; *Grime et al.*, 1999b].

The ages of the Fe meteor trails varied from slightly more than a minute to almost 30 min. The average age is slightly more than 10 min and is strongly altitude dependent. The ages are plotted versus altitude in Fig. 3. The shortest ages are observed below 92 km where chemistry dominates and above 98 km where diffusion dominates. After ablation the Fe trails broaden and the peak density decreases because of diffusion and chemical reactions which form Fe compounds. Eventually the peak density decreases and the trail broadens enough that the trail cannot be reliably distinguished from the background layer. Because molecular diffusivity is inversely proportional to atmospheric density, the primary mechanism for dissipating the trails at high altitudes is diffusion. At low altitudes below 92 km chemical effects dominate. The reaction of Fe with O_3 to form FeO is the primary loss mechanism. In fact, the temperature dependence of this reaction is responsible for the large seasonal variation in the abundance of the background Fe layer at mid-latitudes [*Kane and Gardner*, 1993a; *Helmer et al.*, 1998].

Fig. 3

The mean altitude of the 18 Fe meteor trails is 95.67 $\pm$ 0.93 km and the RMS width of the distribution is 3.93 $\pm$ 0.65 km. *Kane and Gardner* [1993b] characterized 101 Na and Fe sporadic meteor trails. They reported a mean altitude of 89.0 $\pm$ 0.3 km and an RMS width of 3.3 $\pm$ 0.2 km. On 16-17 Nov 1996, Hoffner et al. [1999] observed 9 Leonid and sporadic meteor trails with a K lidar. They reported a mean altitude of 88.4 $\pm$ 1.6 km and an RMS width of 4.8 $\pm$ 1.1 km. *Von Zahn et al.* [1999] observed 3 Leonid trails during the 1998 shower with an Fe lidar and found the mean altitude to be 99.7 km. *Chu et al.* [1999] also observed 7 persistent trails during the 1998 shower with a Na lidar at the Starfire Optical Range, NM. The mean altitude was 94.0 $\pm$ 1.6 km. The altitudes of the 1998 Leonid Fe and Na trails are significantly higher than the sporadics reported by *Kane and Gardner* [1993b]. The difference in mean altitude reported here for the Fe trails and in *Kane and Gardner* [1993b] is 6.7 $\pm$ 0.98 km. This difference is probably associated with the higher entry speeds of the Leonid (72 km/s) compared to sporadics (~30 km/s) and implies that a significant percentage of the observed trails are from Leonid meteors. If we assume that a meteor begins to ablate when the kinetic energy imparted to the atmosphere reaches a critical threshold (KE $\sim \rho_A V^2$), then the altitude difference for ablation is given approximately by

$$\Delta z \approx 2H \ln(V_1/V_2) \qquad (2)$$

where $\rho_A \propto e^{-z/H}$ is the atmospheric density, $H \approx 5$km is the atmospheric scale height. V_1 = 72 km/s, and

$V_2 \approx 30$ km/s. This simple model predicts a difference of 8.8 km and is consistent with the observations.

Summary

The 18 Fe ablation trails observed during the 1998 Leonid meteor shower provide a reasonably good statistical description of the meteoroid characteristics and their effects on the mesopause region of the atmosphere. We did not detect any apparent change in the background Fe layer caused by the unusually large influx of debris during the 1998 Leonid shower. The average age of the trails, determined using a molecular diffusion model, is just over 10 min and is strongly altitude dependent. The shortest ages were observed below 92 km where chemical reactions remove atomic Fe and above 98 km where molecular diffusion rapidly dissipates the trails. Because of the high velocity of the aircraft, it was possible to observe a larger horizontal region of the atmosphere and so the meteor detection rate was much larger than that expected for a groundbased lidar. All 18 Fe trails were detected within a 5.5 h period during the flight for a detection rate of 3.3/h. *Von Zahn et al.* [1999] report a Leonid meteor detection rate of about 1/h using a groundbased K/Fe lidar. The aircraft speed (~150 m/s) is roughly 3 to 5 times faster than typical horizontal wind velocities at mesopause altitudes which appears to account for the differences in the detection rates.

The high velocity Leonid meteors ablate on average about 6.7 km higher than the slower sporadics. This altitude difference is consistent with the assumption that ablation occurs when the kinetic energy imparted to the atmosphere by the meteor reaches a critical level. Under this assumption, faster meteors ablate at higher altitudes where the atmospheric density is lower.

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References

Chu, X., Alan Liu, George Papen, Chester S. Gardner, Jack Drummond, and Peter Jenniskens, Initial radii of the Na ablation trails associated with bright Leonid fireballs, *Geophys. Res. Lett.*, submitted October 1999.

Gelbwachs, J. A., Iron Boltzmann factor LIDAR: proposed new remote-sensing technique for mesospheric temperature, *Appl. Opt.*, *33*, 7151-7156, 1994.

Grime, B. W., Kane, T. J. et al, Meteor trail advection and dispersion; preliminary observations, *Geophys. Res. Lett.*, *26*, 675-678, 1999a.

Grime, B. W., Kane, T. J. et al., Meteor trail advection observed during the 1998 Leonid shower, *J. Geophys. Res.*, submitted October 1999b.

Helmer, M., J. M. C. Plane, J. Qian, and C. S. Gardner, A Model of Meteoric Iron in the Upper Atmosphere, *J. Geophys. Res.-Atmospheres*, *103*, 10913-10926, 1998.

Hoffner, J., U. von Zahn, W. J. McNeil, and E. Murad, The 1996 Leonid shower as studied with a potassium lidar: Observations and inferred meteoroid sizes, *J. Geophys. Res.*, *104*, 2633-2643, 1999.

Jenniskens, P. and S. Butow, The 1998 Leonid Multi-Instrument Aircraft Campaign, *Meteor. & Planet. Sci.*, in press, 1999.

Jones W., On the initial radius of meteor trains, *Mont. Not. R. Astron. Soc.* *275*, 812-818, 1995.

Kane, T. J. and C. S. Gardner, Structure and seasonal variability of the nighttime mesospheric Fe layer at midlatitudes, *J. Geophys. Res.*, *98*, 16875-16886, 1993a.

Kane, T. J. and C. S. Gardner, Lidar observations of the meteoric deposition of mesospheric metals, *Science*, *259*, 1297-1300, 1993b.

Von Zahn, U., M. Gerding, J. Hoffner, W. J. McNeil, and E. Murad, Fe, Ca, and K atom densities in the trails of Leonid and other meteors: Strong evidence for differential ablation, *Meteor. & Planet. Sci.*, in press, 1999.

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Figure 1. Fe meteor trail profile probed by the airborne lidar at 18:48:26 (UT) on 17 November 1998 over Okinawa. The vertical resolution is 24 m and integration period is 10 s. The dense narrow layer at 94.8 km is a meteor ablation trail, while the broader layer at 91 km is a sporadic Fe layer.

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Figure 2. Average abundances of the background Fe layer measured during 1998 Leonid MAC on and off the peak night versus local date for November 1998. The abundances were computed between 0200 and 0400 LT to minimize biases associated with tides and other diurnal effects. The observations with meteor trails were excluded.

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Figure 3. Figure 3. Altitude distribution of Fe meteor trail ages. The shortest ages are observed below 92 km where chemistry dominates and above 98 km where diffusion dominates.

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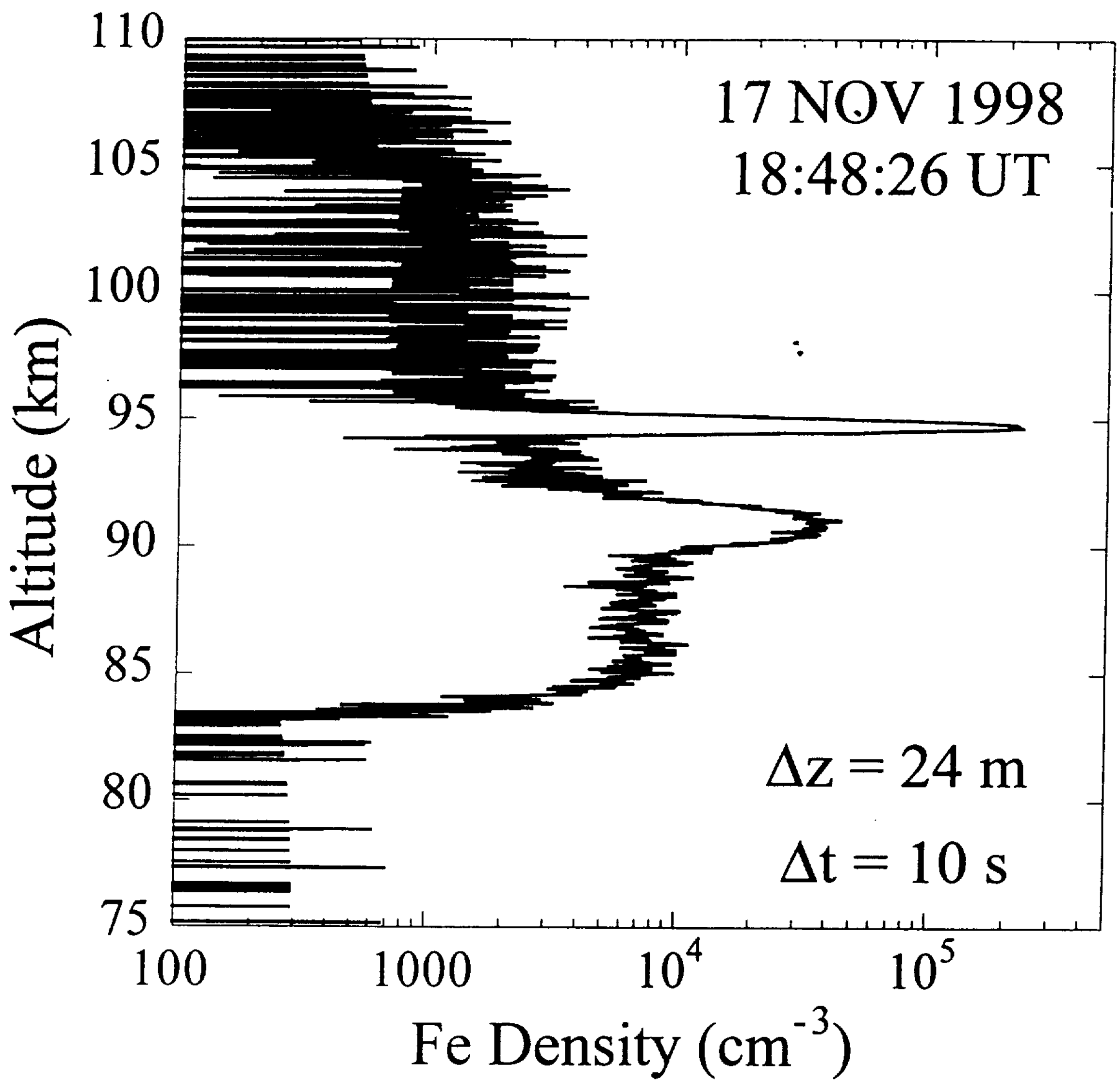
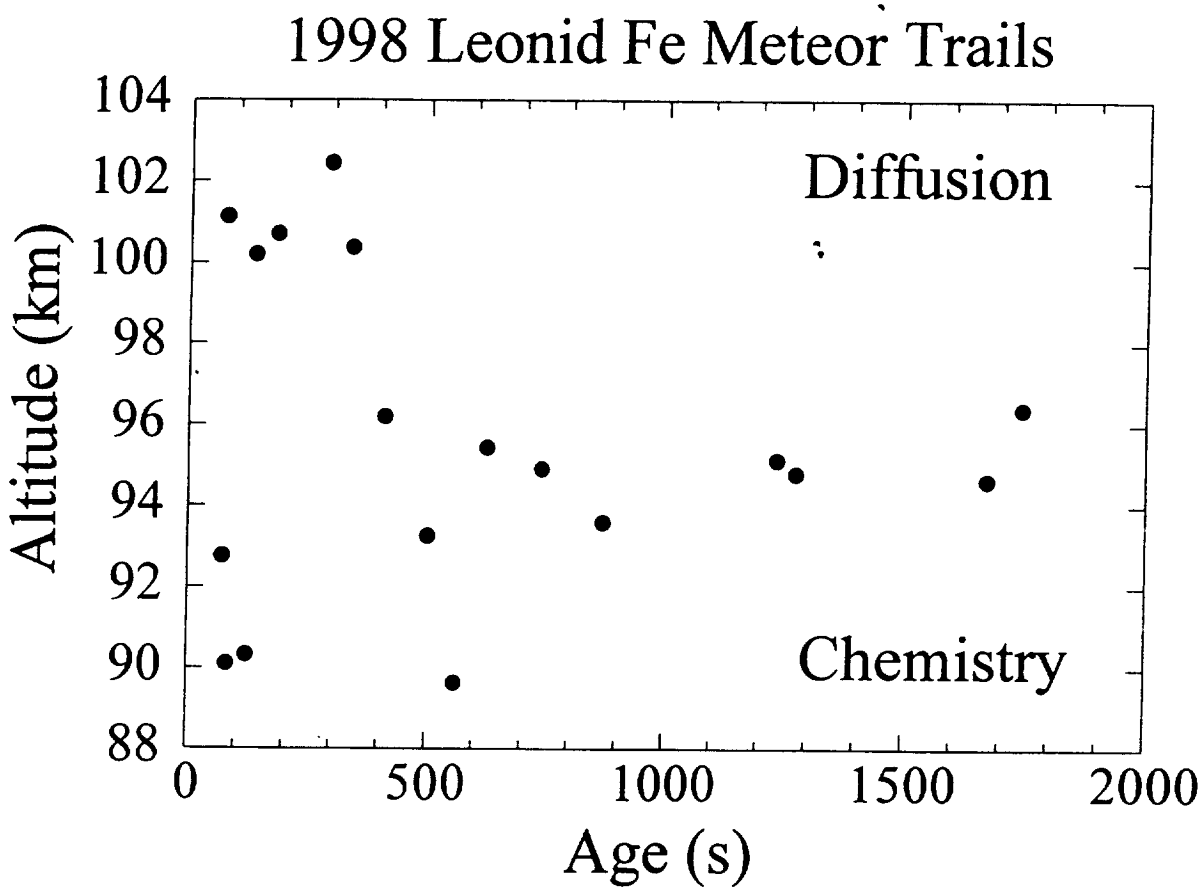
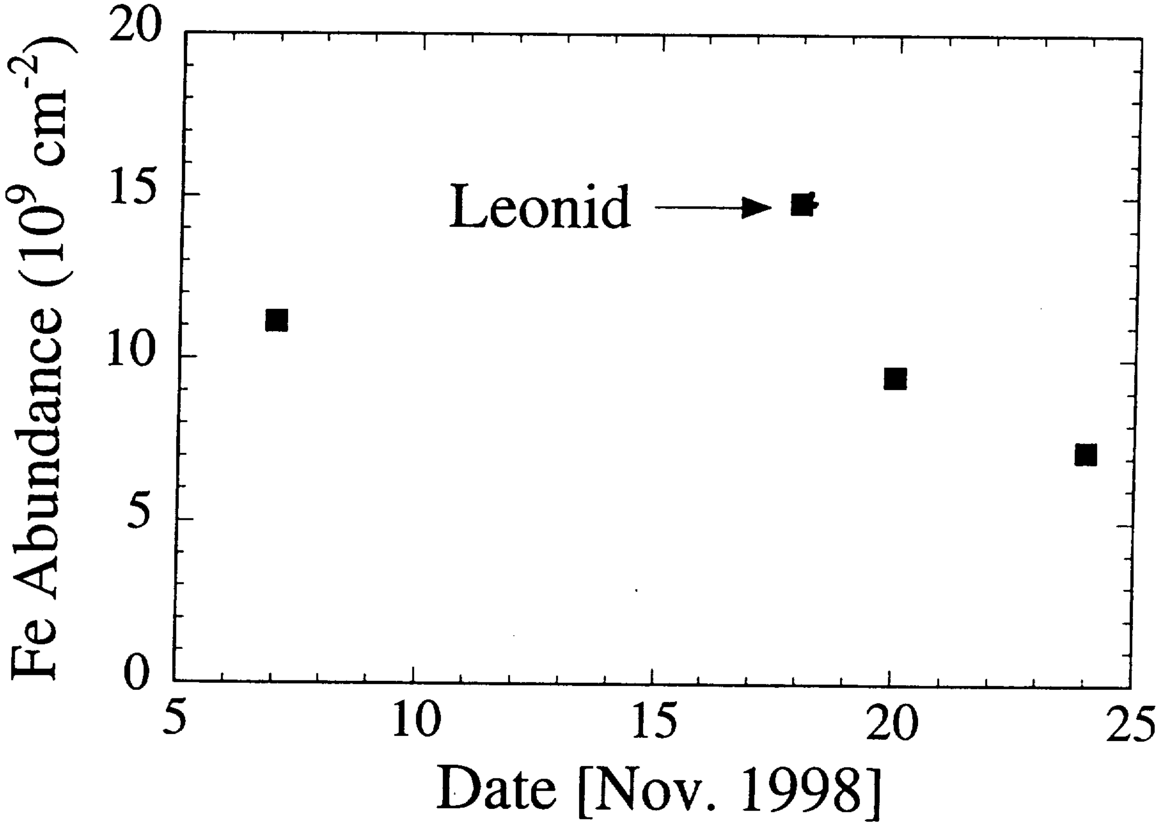
Table 1. Characteristics of the 1998 Leonid Fe meteor trails

Event	Estimated Ablation Time (UT)	Peak Density Time (UT)	Duration (s)	Altitude (km)	Meteor Abundance ($10^9 cm^{-2}$)	Background Abundance ($10^9 cm^{-2}$)	Meteor Peak Density ($10^3 cm^{-3}$)	RMS Width (m)	Ag… (s…
1	15:44:43	15:45:54	10	92.76	> 0.048	4.50	10.8	29±2	71±
2	15:44:23	15:46:25	10	90.33	> 0.090	4.73	14.7	31±4	122±
3	16:55:34	17:04:55	20	89.63	0.69	8.11	51.3	62±3	561±
4	17:05:45	17:06:59	10	101.14	> 0.56	9.41	32.7	63±5	74±
5	17:05:15	17:07:30	30	100.20	0.24	8.06	16.6	78±19	135±
6	17:02:38	17:17:09	60	93.58	0.41	7.95	21.6	110±15	871±
7	17:23:58	17:25:21	10	90.12	> 0.10	14.0	23.5	25±6	83±
8	18:27:09	18:48:26	50	94.80	8.60	12.0	233	148±2	1277±
9	19:45:58	19:50:50	20	102.45	0.91	8.13	26.3	139±5	292±
10	19:49:17	19:54:55	90	100.38	0.54	8.89	20.5	125±5	338±
11	19:38:02	20:07:05	20	96.39	0.93	8.26	25.8	200±17	1743±
12	20:08:17	20:11:18	20	100.71	0.71	8.14	31.4	94±4	181±
13	20:49:32	20:56:23	110	96.19	2.75	13.5	111	95±2	411±
14	20:50:01	21:00:26	40	95.42	0.60	13.2	25.2	109±5	625±6
15	20:40:41	21:01:18	50	95.13	0.57	13.6	21.7	151±6	1237±
16	20:49:29	21:01:50	50	94.89	0.50	13.4	20.0	113±5	741±
17	20:53:28	21:01:50	50	93.25	0.26	13.4	19.5	81±5	502±
18	20:34:52	21:02:43	20	94.63	0.63	12.3	19.8	167±8	1671±
Mean			37	95.67±0.93	1.06	10.1	40.3	101	608
Std			28	3.93±0.65	1.97	3.11	53.0	49	546



17 NOV 1998
18:48:26 UT
Δz = 24 m
Δt = 10 s
Altitude (km)
110
105
100
95
90
85
80
75
100
1000
10^4
10^5
Fe Density (cm^{-3})


1998 Leonid Fe Meteor Trails
Diffusion
Chemistry
Altitude (km)
104
102
100
98
96
94
92
90
88
0
500
1000
1500
2000
Age (s)


Fe Abundance (10^9 cm^{-2})
Leonid
Date [Nov. 1998]
0
5
10
15
20
25